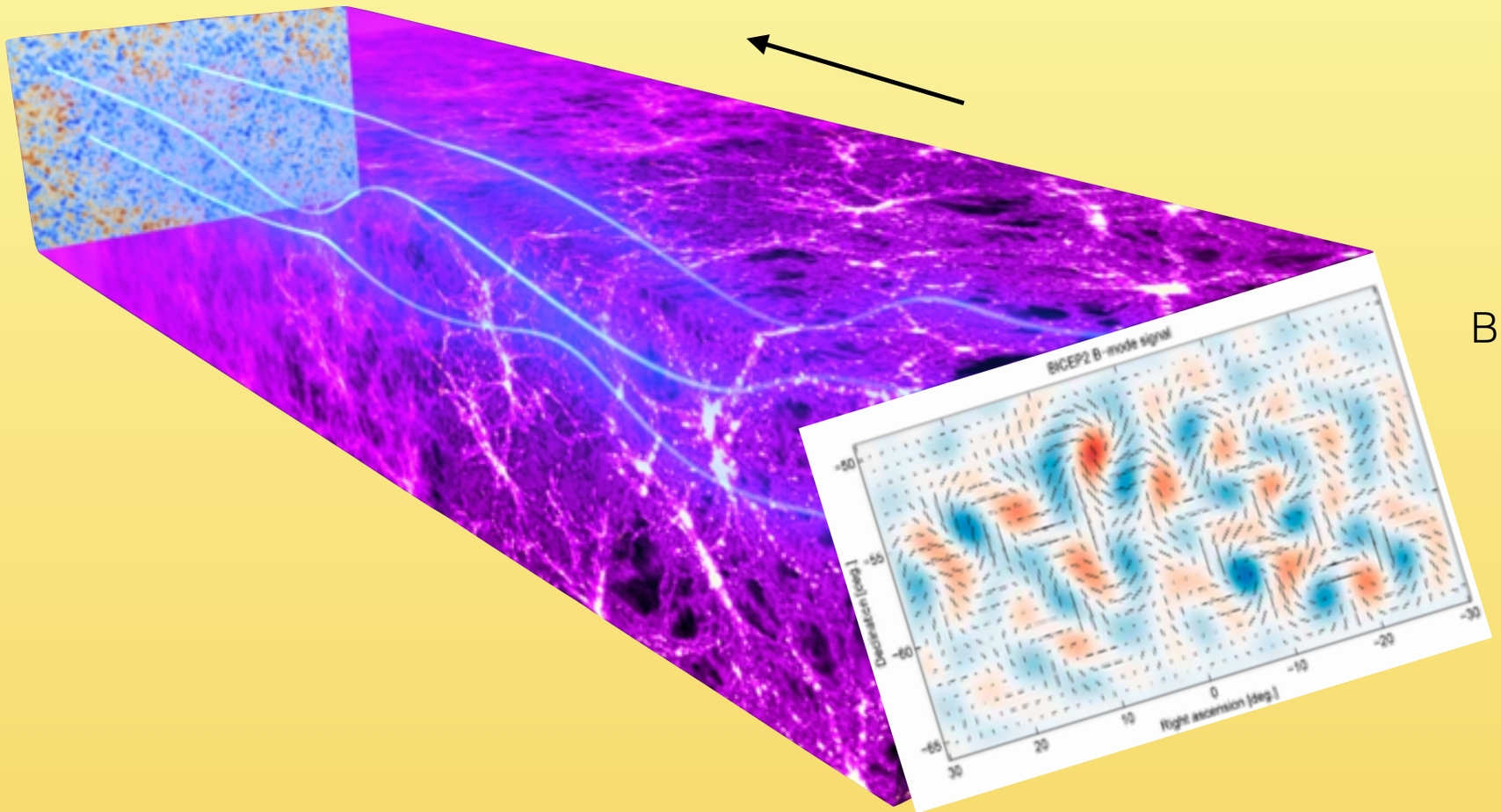
Kavli Institute
for Cosmological Physics
at The University of Chicago

DELENSING OF THE CMB: Present and Future



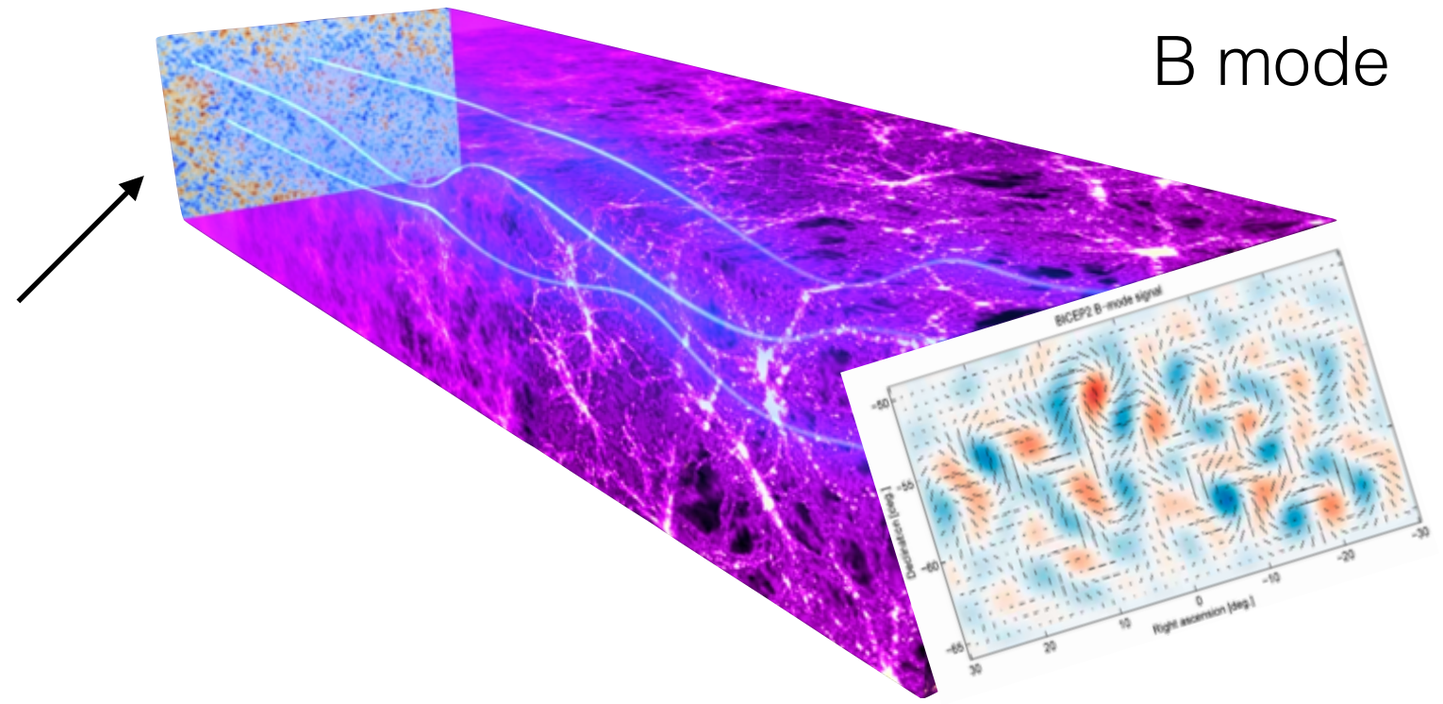
Alessandro Manzotti (KICP-U. Chicago)

w. K. Story K. Wu and the SPT collaboration

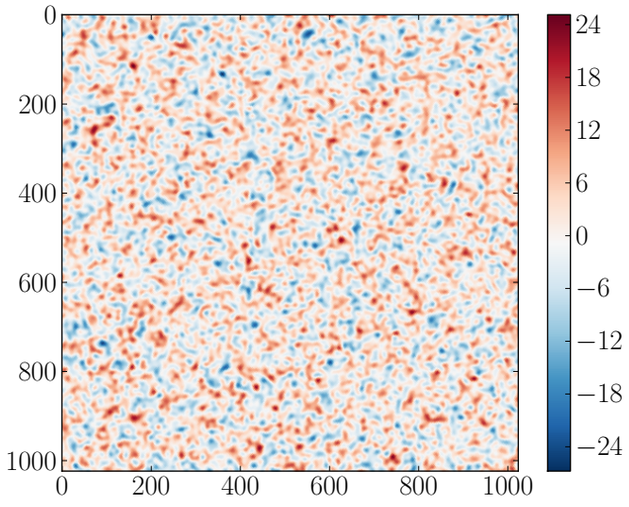
WHAT IS DELENSING?

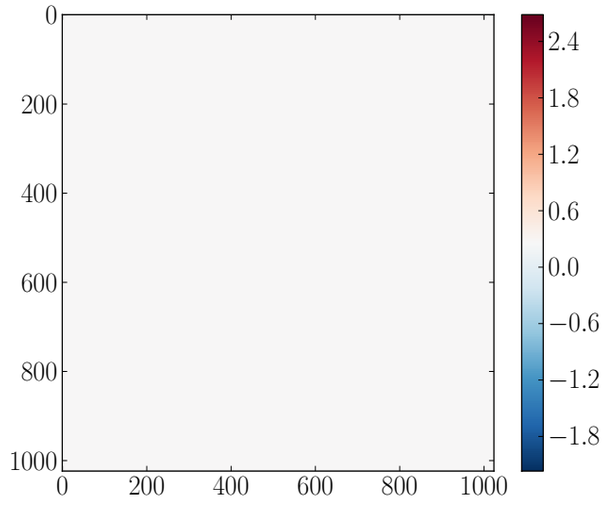
E mode

B mode



$12° \times 12°$



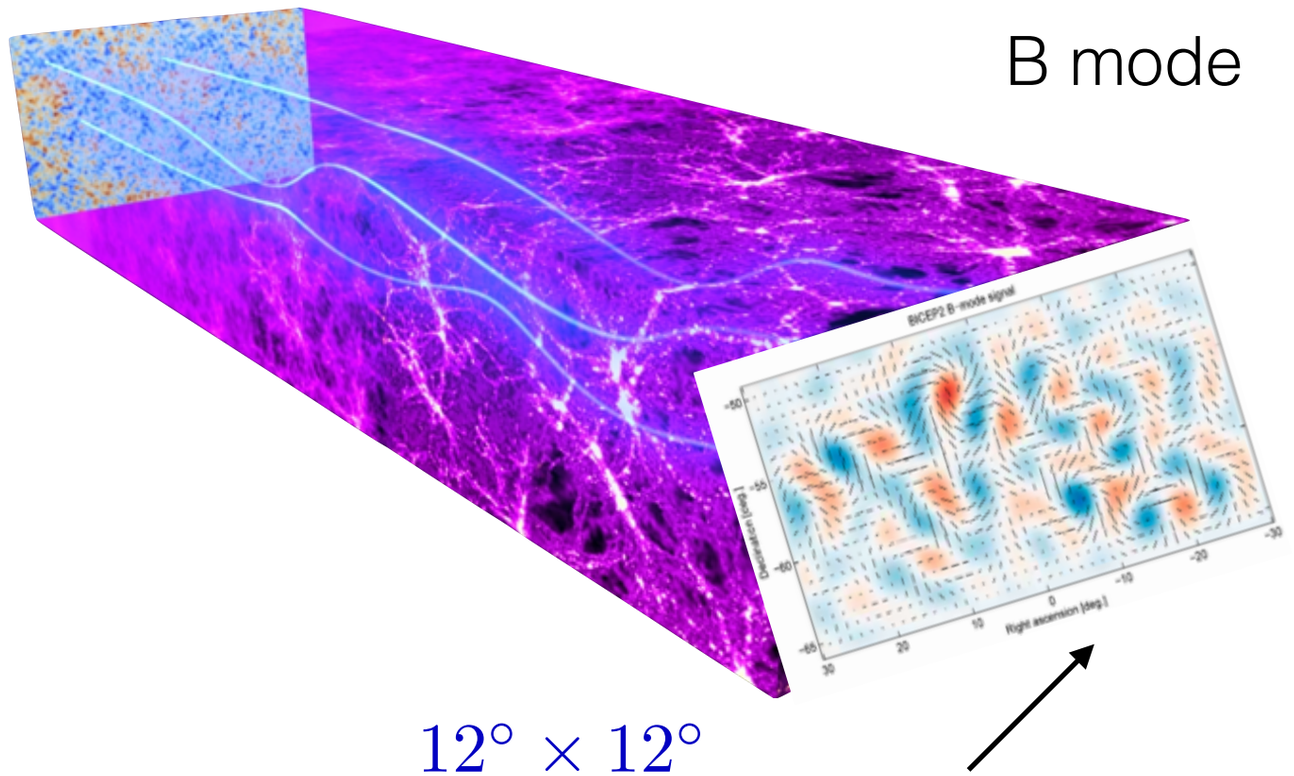


E mode μK B mode

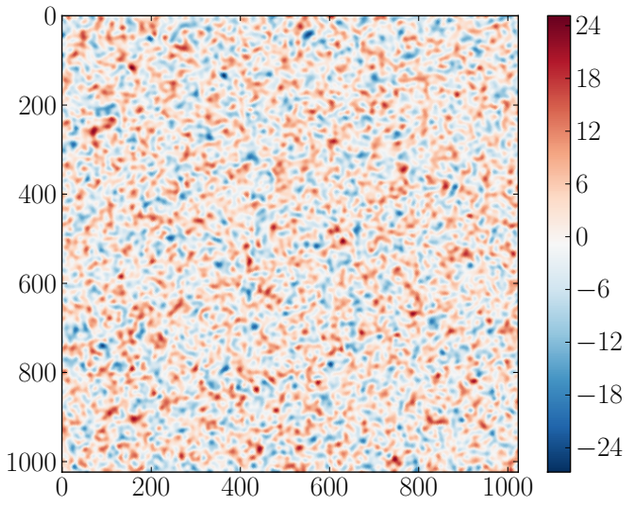
E-B DECOMPOSITION IS NOT PRESERVED BY LENSING

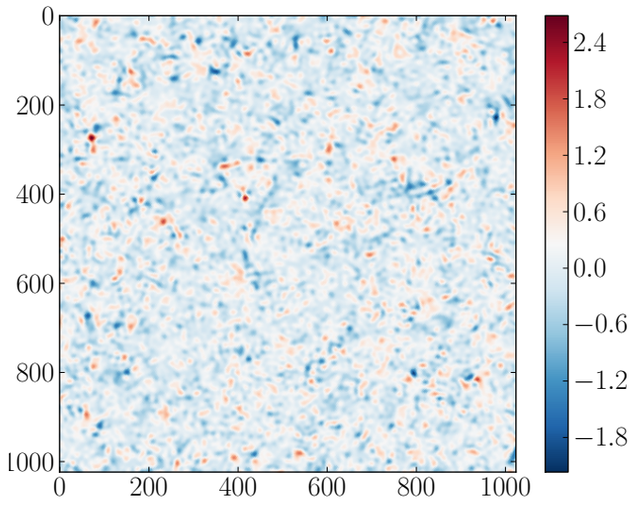
E mode

B mode



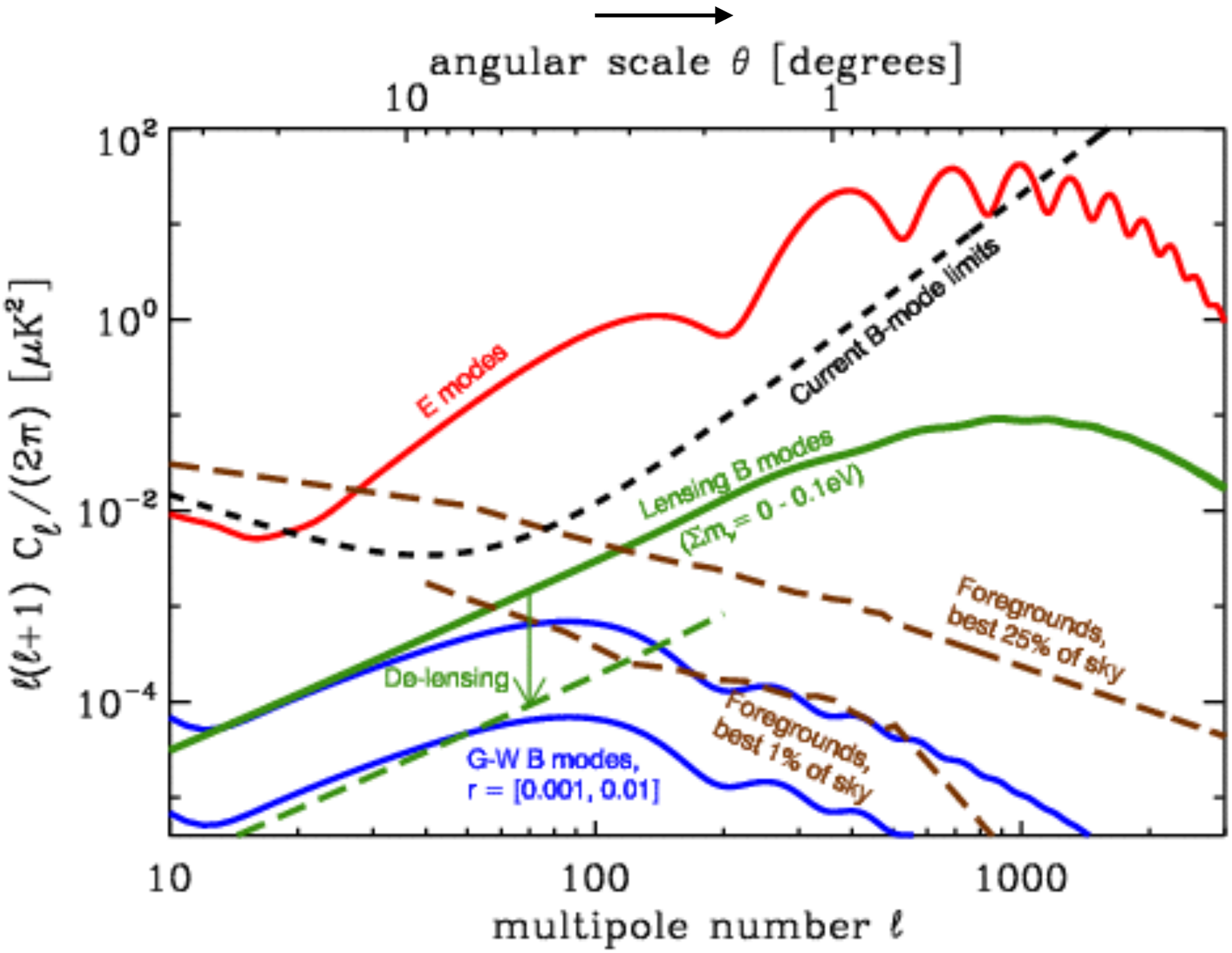
$12° \times 12°$





E mode μK B mode

B-MODE LENSING SPECTRUM



Power

Abazajian, K.N. *et al.*

MESSAGE: DELENSING IS CRUCIAL, IT IS HARD AND WE ARE WORKING ON IT

CRUCIAL: IT WILL LIMIT INFLATIONARY CONSTRAINTS AND MORE

In 10 years (CMB Stage 4) it could be the main source of noise for primordial B mode signal.

- Our constraint on the **inflationary tensor** perturbation **amplitude and tilt** will depend on it
- It will **limit lensing reconstruction** (see iterative delensing)
- It will **limit constraints** on parameters that **affect peak position and damping of the CMB** like N_eff.

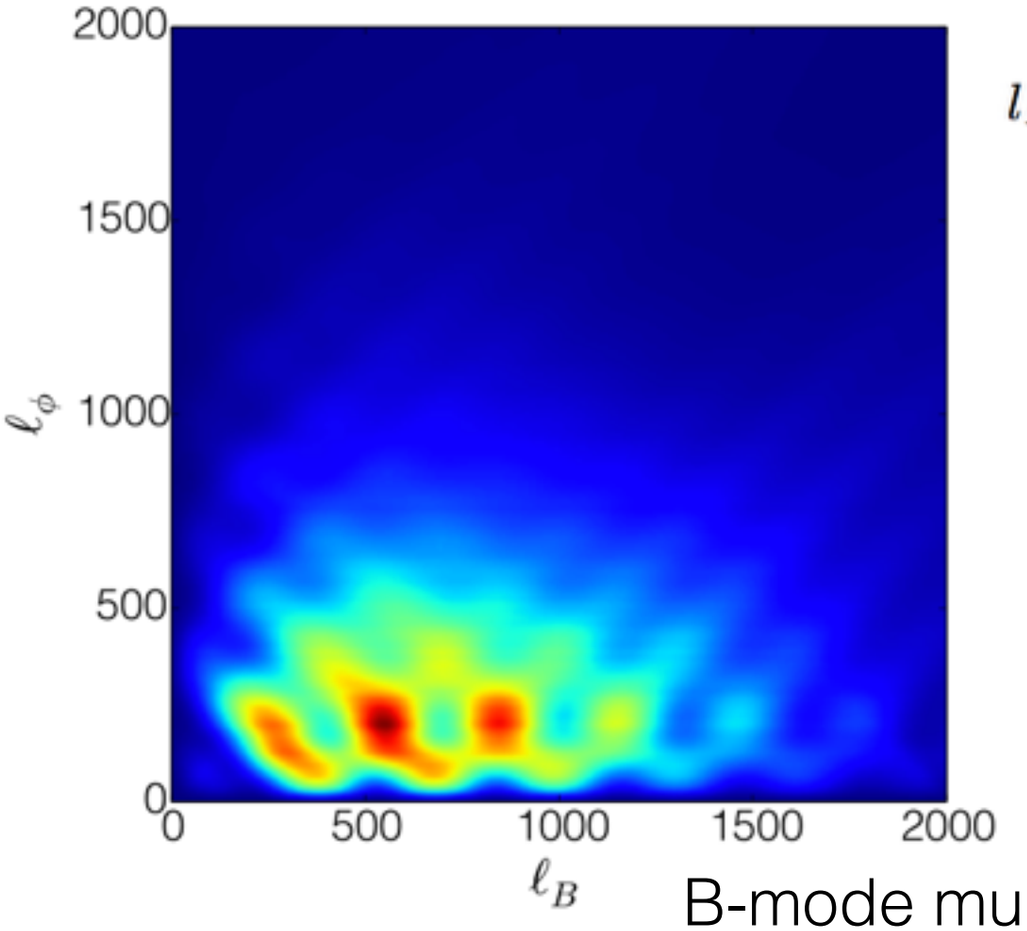
WHAT CAN WE DO?

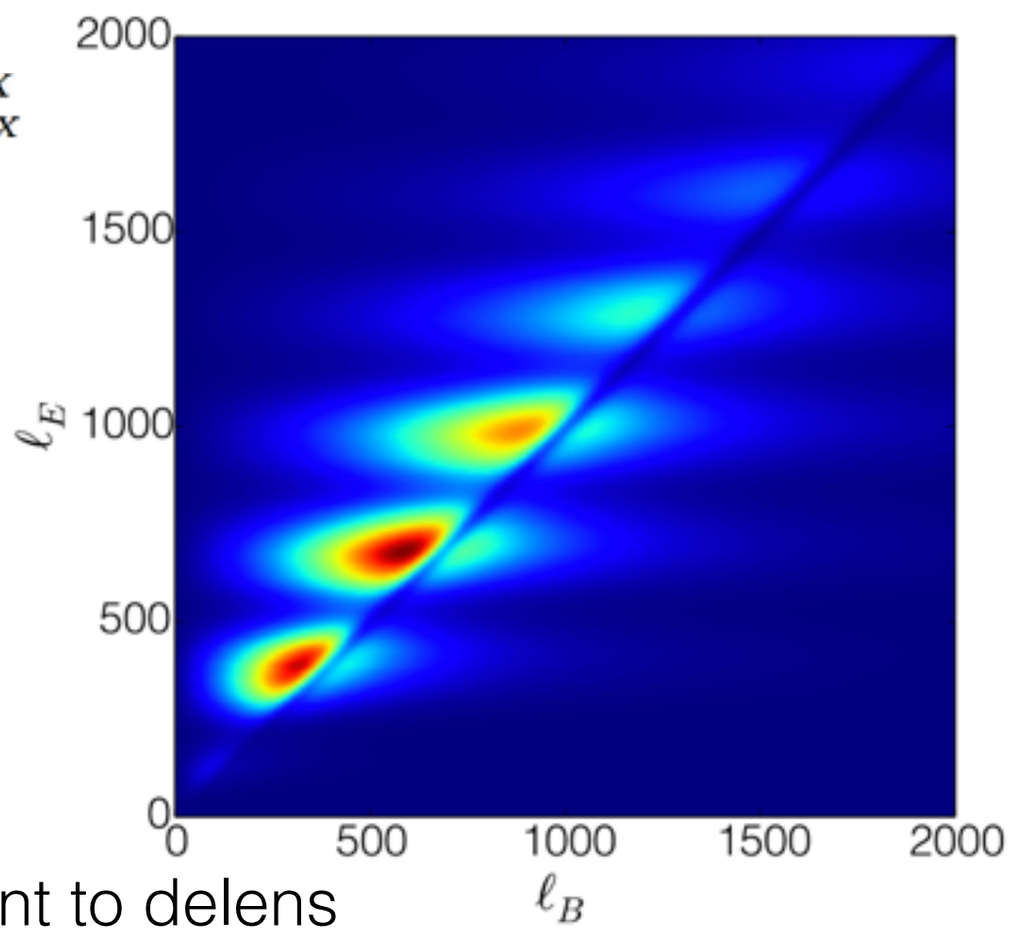
- It is an almost **white noise component** at **~5 uK-arcmin**.
- **Not** cleanable with **multi frequencies**.
- Well **modeled** but **cosmic variance** would be a **problem** for deep survey.

WHAT CAN WE DO? BUILD A TEMPLATE AND REMOVE

$$E \otimes \phi = B_{lens}$$

$$l_B(\partial C_{l_B}^B / \partial C_{l_X}^X) C_{l_X}^X$$





B-mode multipole you want to delens

Simard,Hanson,Holder 2014

- Mainly from large scale potential l>100
- E_mode from scales smaller than B_lens

E (FROM HIGH-RES CMB) - PHI FROM CIB,CMB,LSS

$$E \otimes \phi = B_{lens}$$

We want

Kernel overlap

Low Noise

CIB

Cosmic Infrared Background

The **best method right now.** Already used on data by SPT (Hanson B-modes paper). CIB model uncertainties not limiting now, you can marginalize over it (Sherwin Schmittfull.). But **can we clean it from dust?**

CMB

In the **future** it will be the **best source** of phi reconstruction. Not there yet but already powerful if combined with the CIB

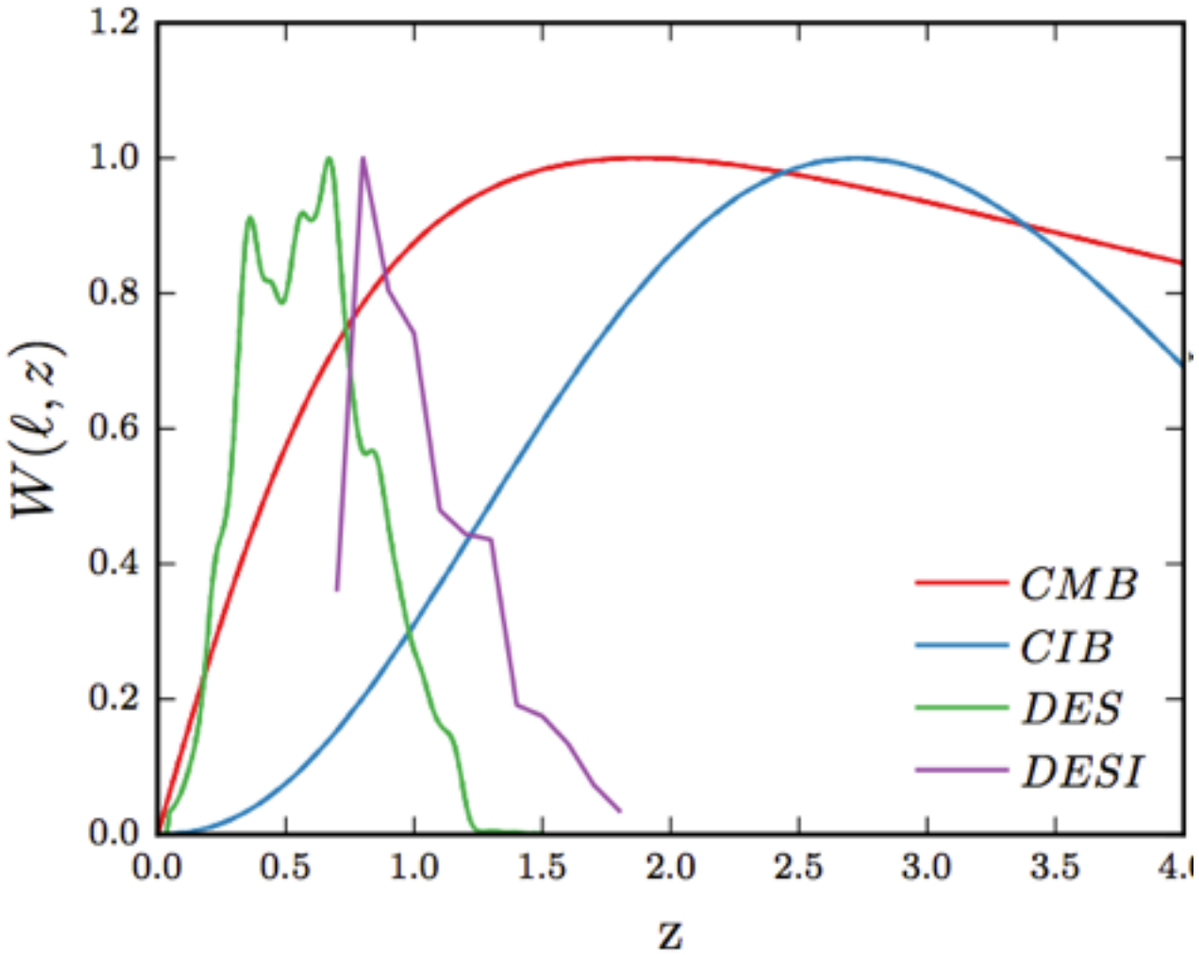
Galaxies

Low redshift. They do not probe well the sources that lens the CMB. But maybe less affected by systematics.

LSST?
SPHEREx
SKA (Namikawa et al.)

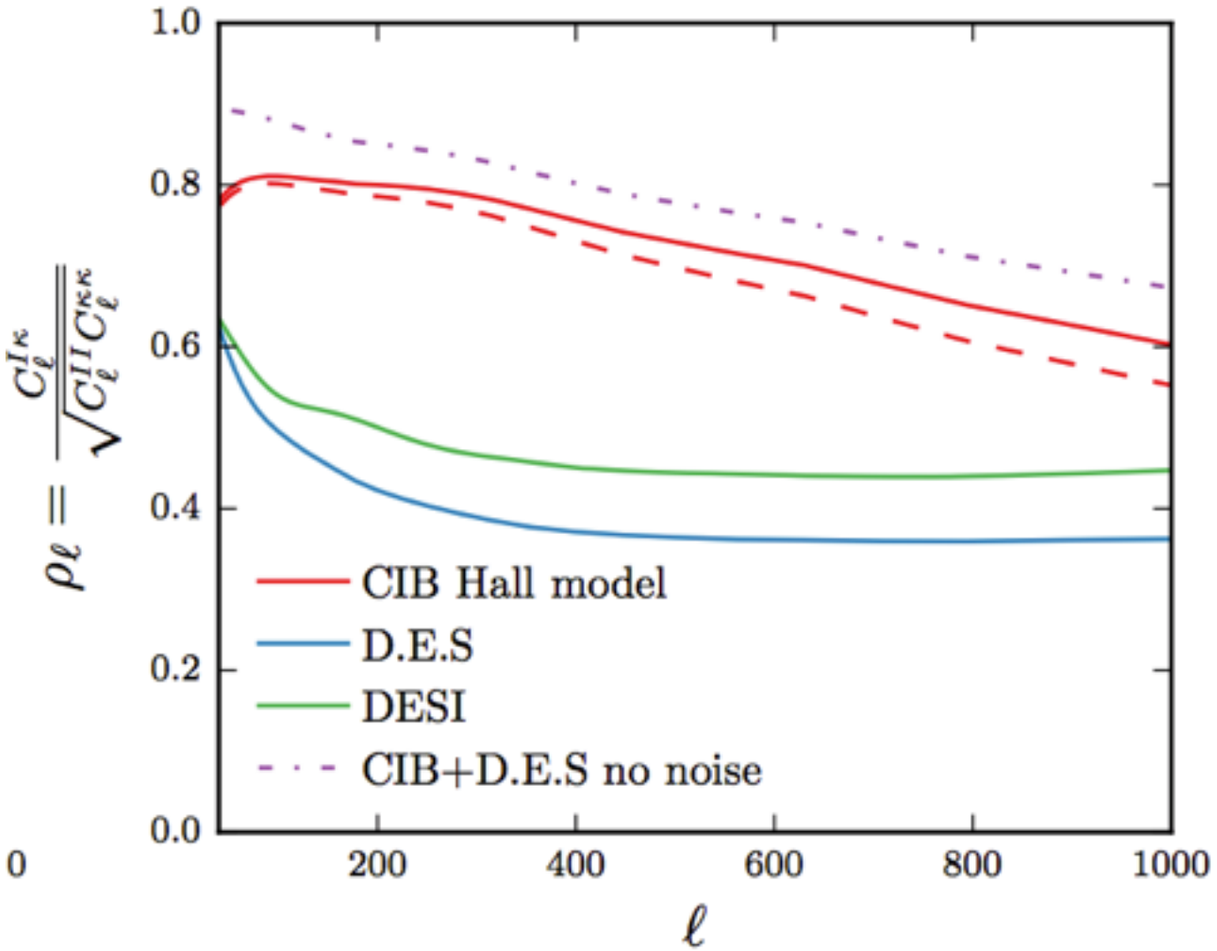
OPTIMAL SOURCE FOR A LENSING MAP?

Where the lenses are



Redshift

How much are they correlated with lensing considering noise

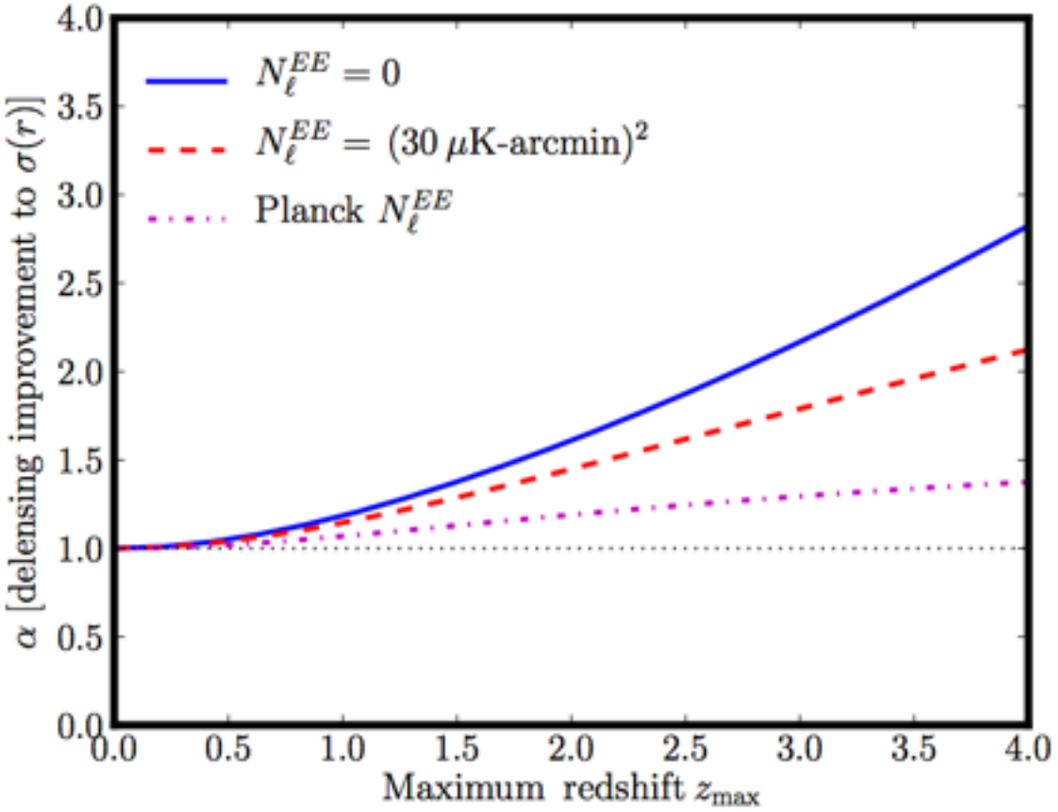


Angular Scale

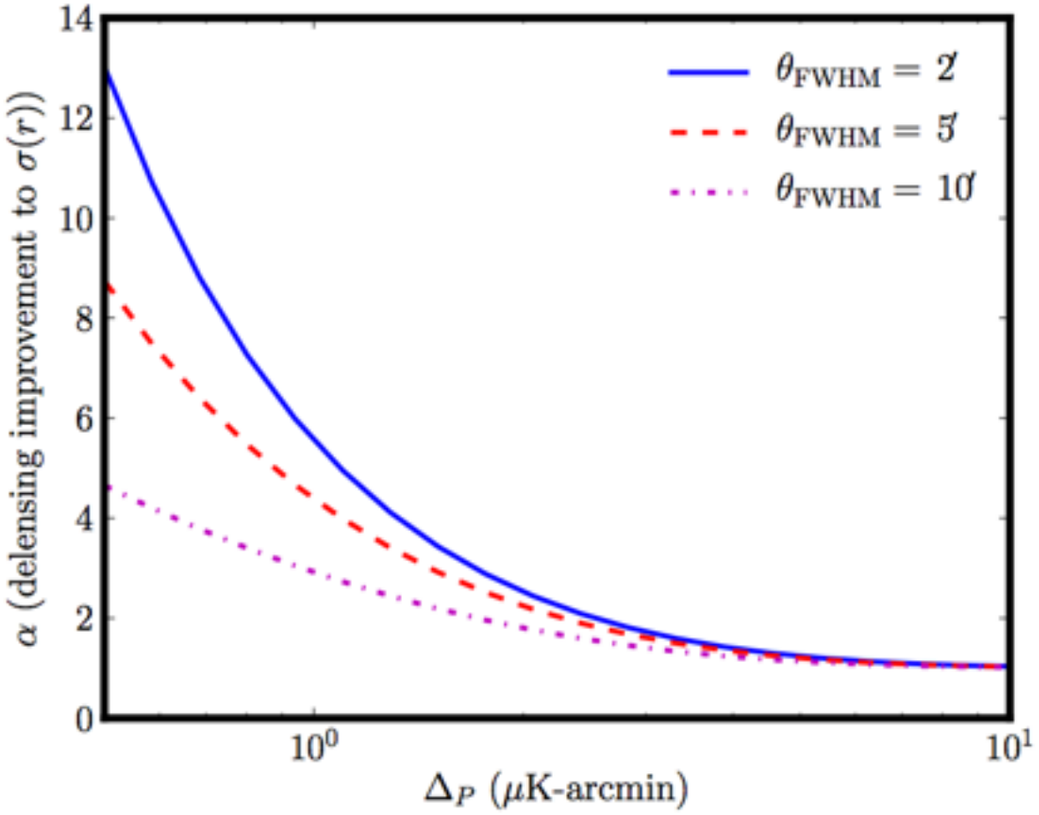
Different tracers can be combined

HOW WELL CAN WE DO?

phi from LSS



phi from CMB EB



Smith et al.

WHAT CAN GO WRONG

- Challenges: **calibrate** CIB (or galaxies). It seems auto-calibration can do it.
- Estimate systematics contamination. Point sources? not a lot of them are polarized. **Dust and synchrotron can be an issue.** Delensing will be performed together with component subtraction.

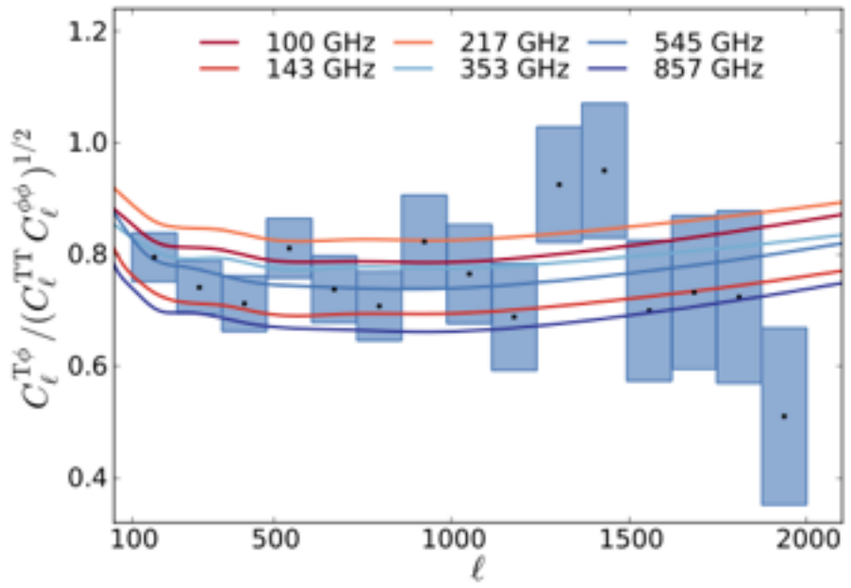
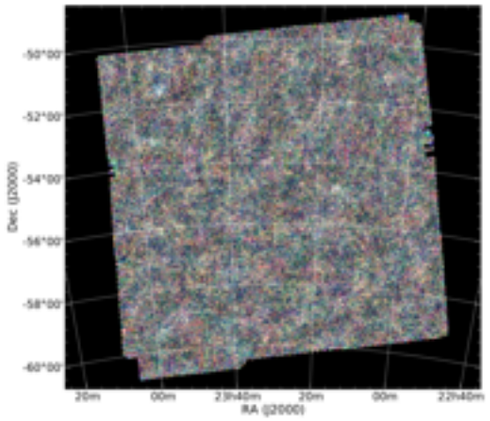
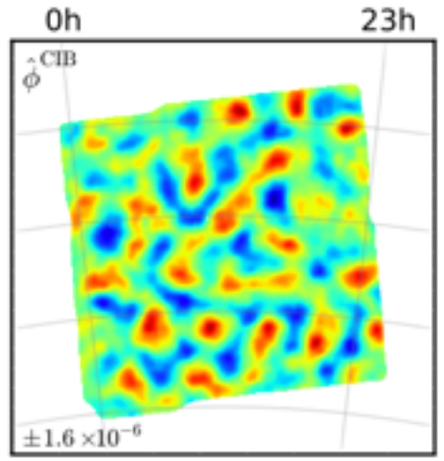


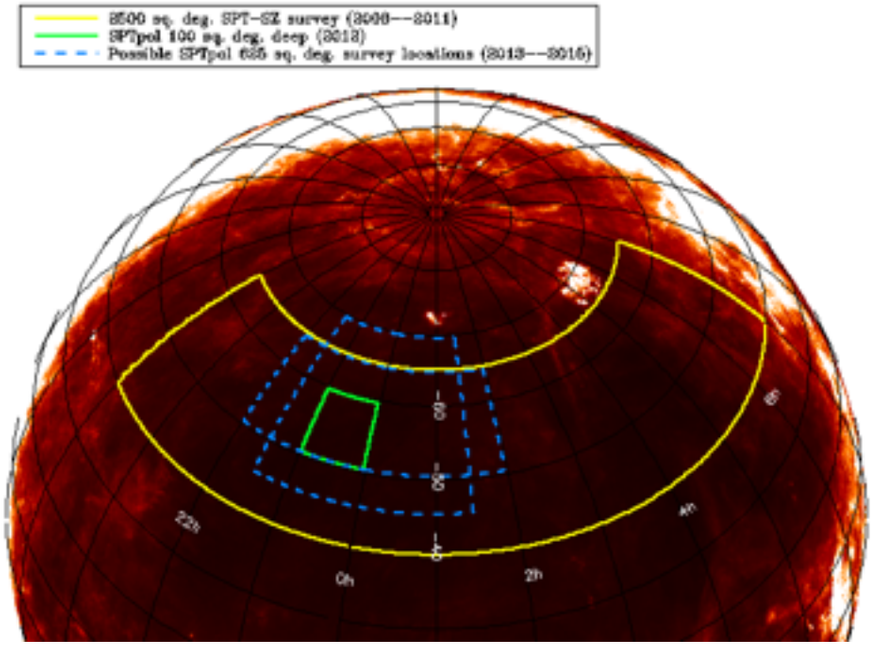
Fig. 13. Cross-correlation coefficients calculated from the model ϕ spectrum and best-fit halo model at each frequency. The CIB is a spectacular tracer of CMB lensing, and vice-versa. The data points represent the measured cross-correlation divided by the best-fit auto power spectra models at 545 GHz.

HARD: THE SPT STORY, DELENSING SPT 100 D

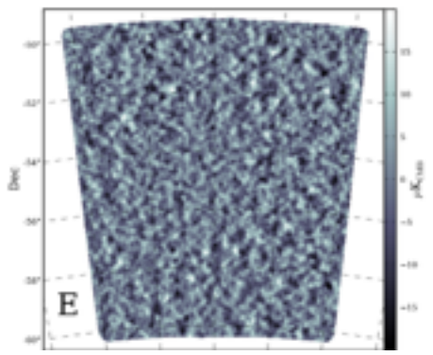
- CIB map from Herschel 500μm map.

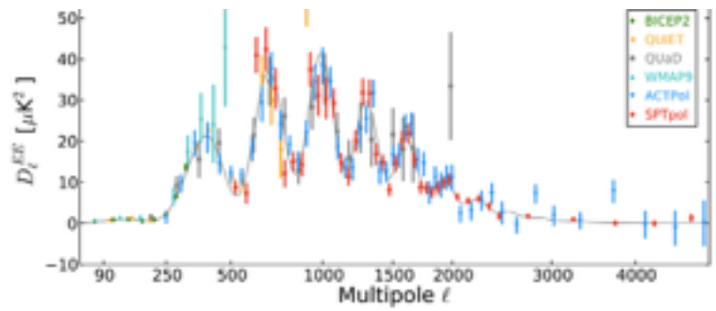




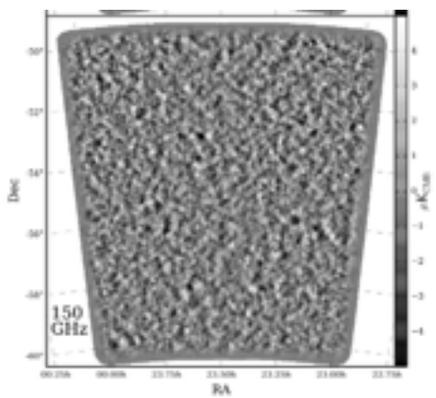


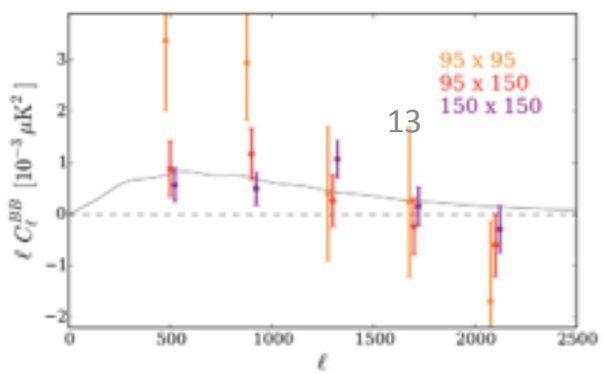
- E mode (Crites, SPT 2015)





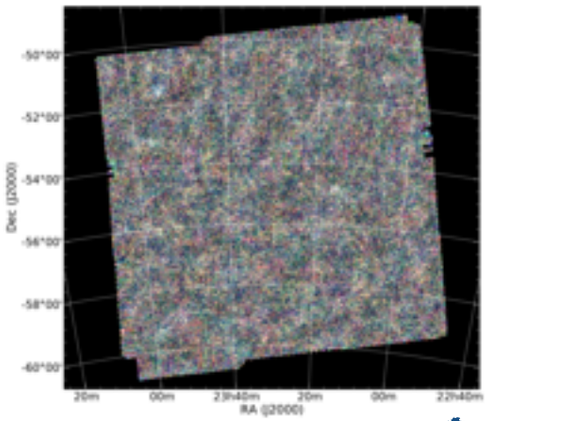
- B mode (Keisler, SPT 2015)

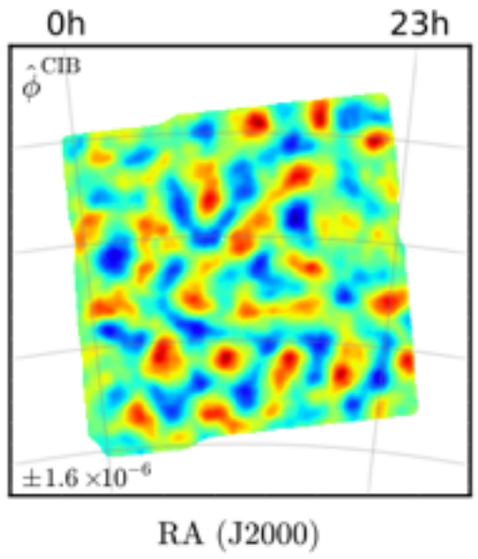


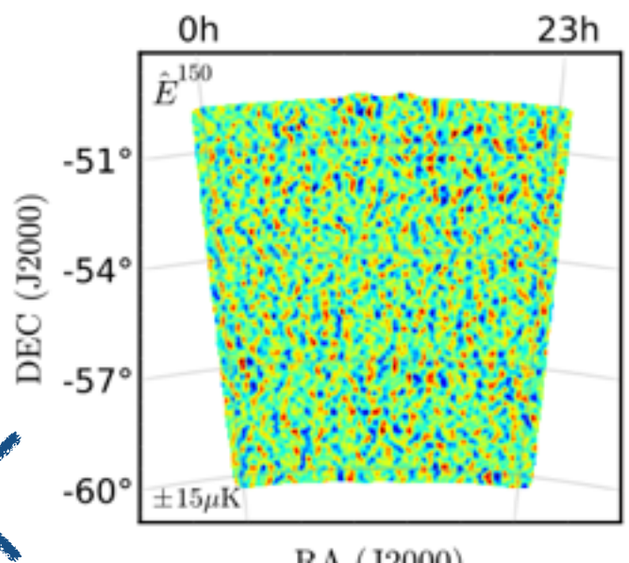


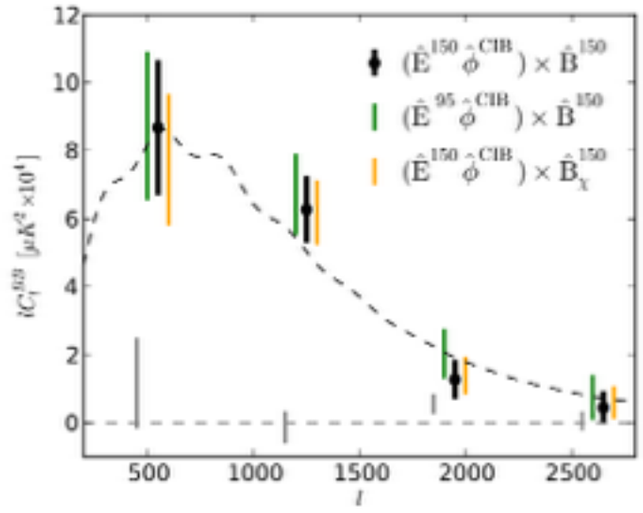
HARD: THE SPT STORY, DELENSING SPT 100 D

- We know the correlation exists.
- But now building a template is not enough if you want to subtract.

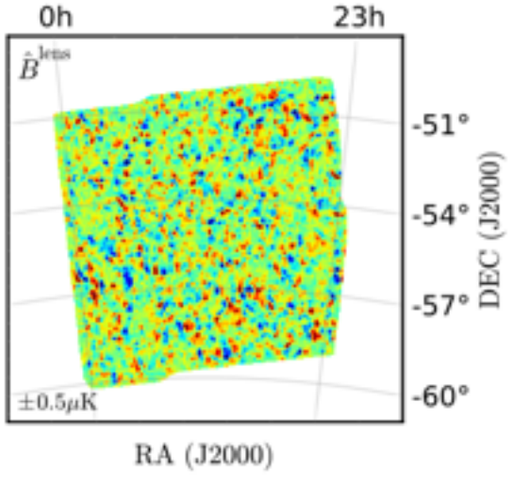








SPT B



D. Hanson, SPT

Alessandro Manzotti KICP Chicago

THE RECIPE

- Construct a lensing map from Herschel CIB data with an optimal estimator

$$\hat{\phi} \;=\; C_\ell^{CIB-\phi}(C_\ell^{\phi\phi}C_\ell^{CIB-CIB})^{-1}\;\; T_\ell^{CIB}$$

- Construct a B-template “lensing” SPT E mode with the lensing map.

$$B^{\rm lens}(\mathbf{l}) = \int \frac{d^2\mathbf{l}'}{(2\pi)^2} W(\mathbf{l},\mathbf{l}')E(\mathbf{l}')\kappa(\mathbf{l}-\mathbf{l}') \qquad W(\mathbf{l},\mathbf{l}') = \frac{2\mathbf{l}'\cdot(\mathbf{l}-\mathbf{l}')}{|\mathbf{l}-\mathbf{l}'|^2}\sin(2\varphi_{\mathbf{l},\mathbf{l}'})$$

- Remove the template from the B mode data map.

$$C_l^{BB,\rm del} = C_l^{BB,r} + C_l^{BB,\rm res} + N_l^{BB}$$

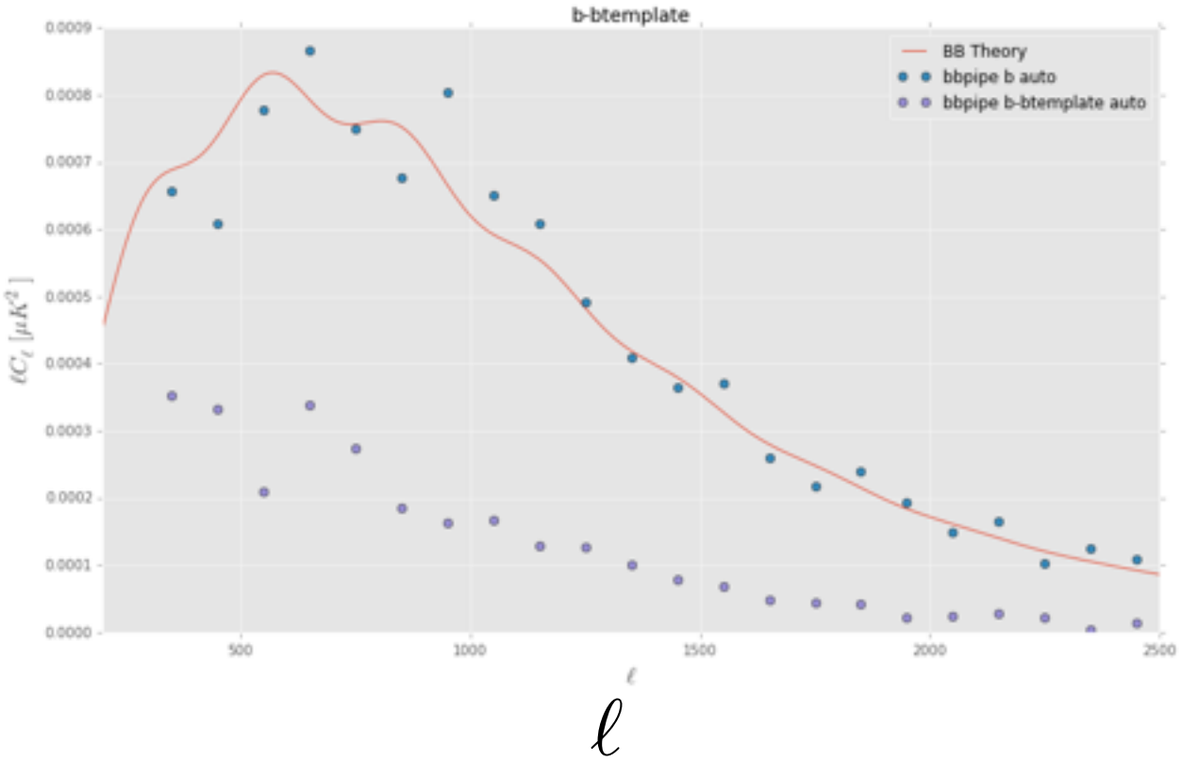
THE CHALLENGES

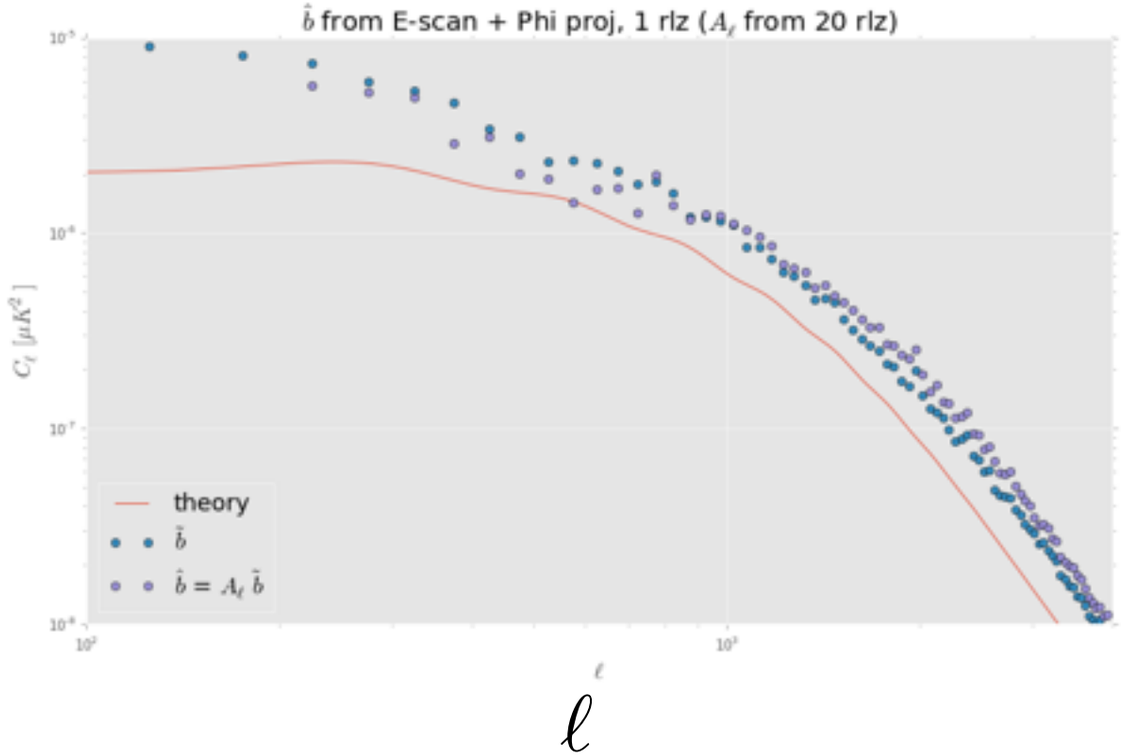
- The **B mode map** and the **B mode template** we want to subtract are coming from different analyses. They have **different filtering, missing modes, different point sources threshold**.

- **Noise Bias**. Due to noise in lensing maps and E-mode, foregrounds, masking and filtering.

- We are **testing** the technique for the **first time** on **data**. **Using** this to improve r constraint **requires** an **unprecedented control of systematics**.

THE PRESENT





It is working on idealized sims (still no instrumental noise).
We observe noise bias and are working to understand it.

THE FUTURE

- Calibrate the template and characterized noise bias. Contribution from lensing map, noise, masking filtering. How does dust and sources propagate through.

- Understand the residual map Statistical and noise properties.

DELENSING IS CRUCIAL, IT IS HARD AND WE ARE WORKING ON IT!
STAY TUNED

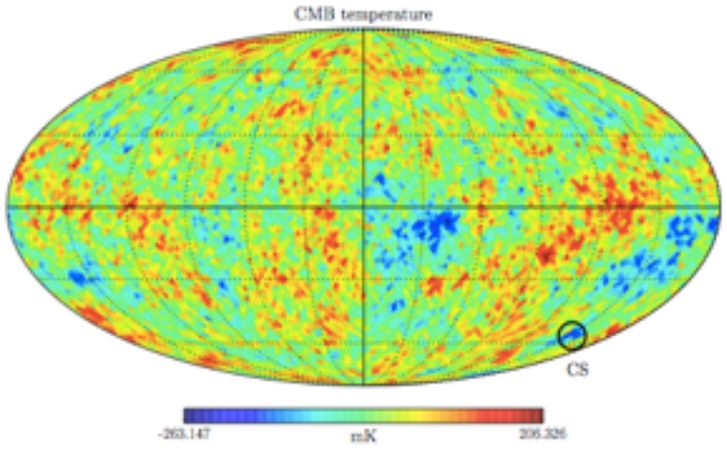
CAN LSS HELP?

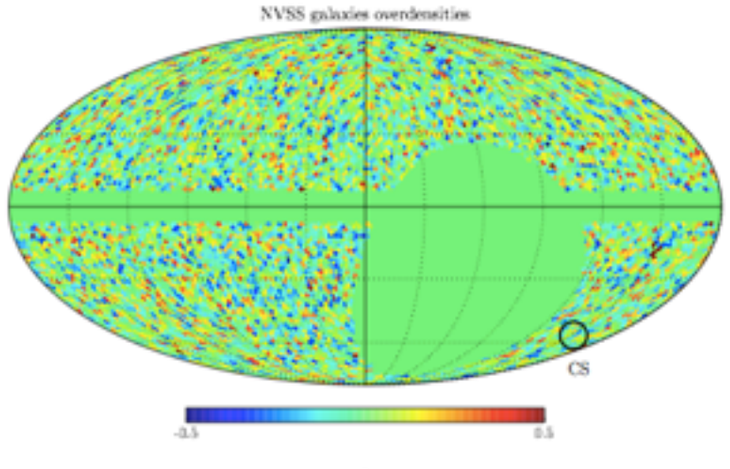
OPTIMAL ESTIMATED MAP

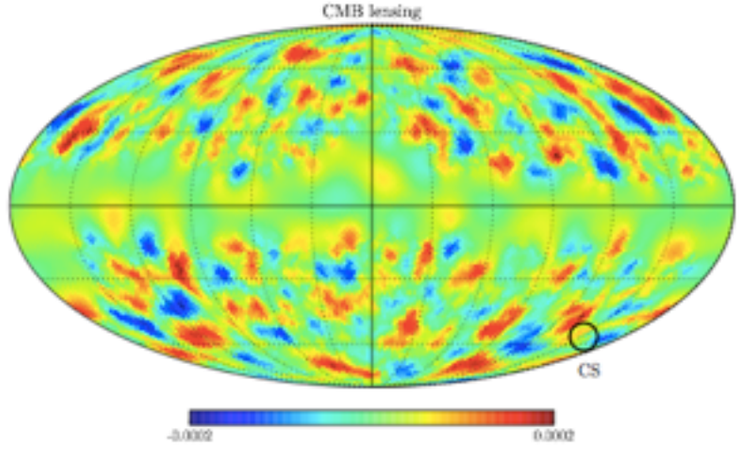
IDEA: YOU WANT TO COMBINE OPTIMALLY DIFFERENT MAPS TO EXTRACT THE BEST ESTIMATED SIGNAL.

- Useful when you need a map. Cross correlation, delensing, anomalies.
- Example: you might imagine to combine different lensing potential maps (CIB + CMB reconstructed + galaxies + …) to improve for example delensing.

WE USED: NVSS, PLANCK LENSING, PLANCK TEMPERATURE





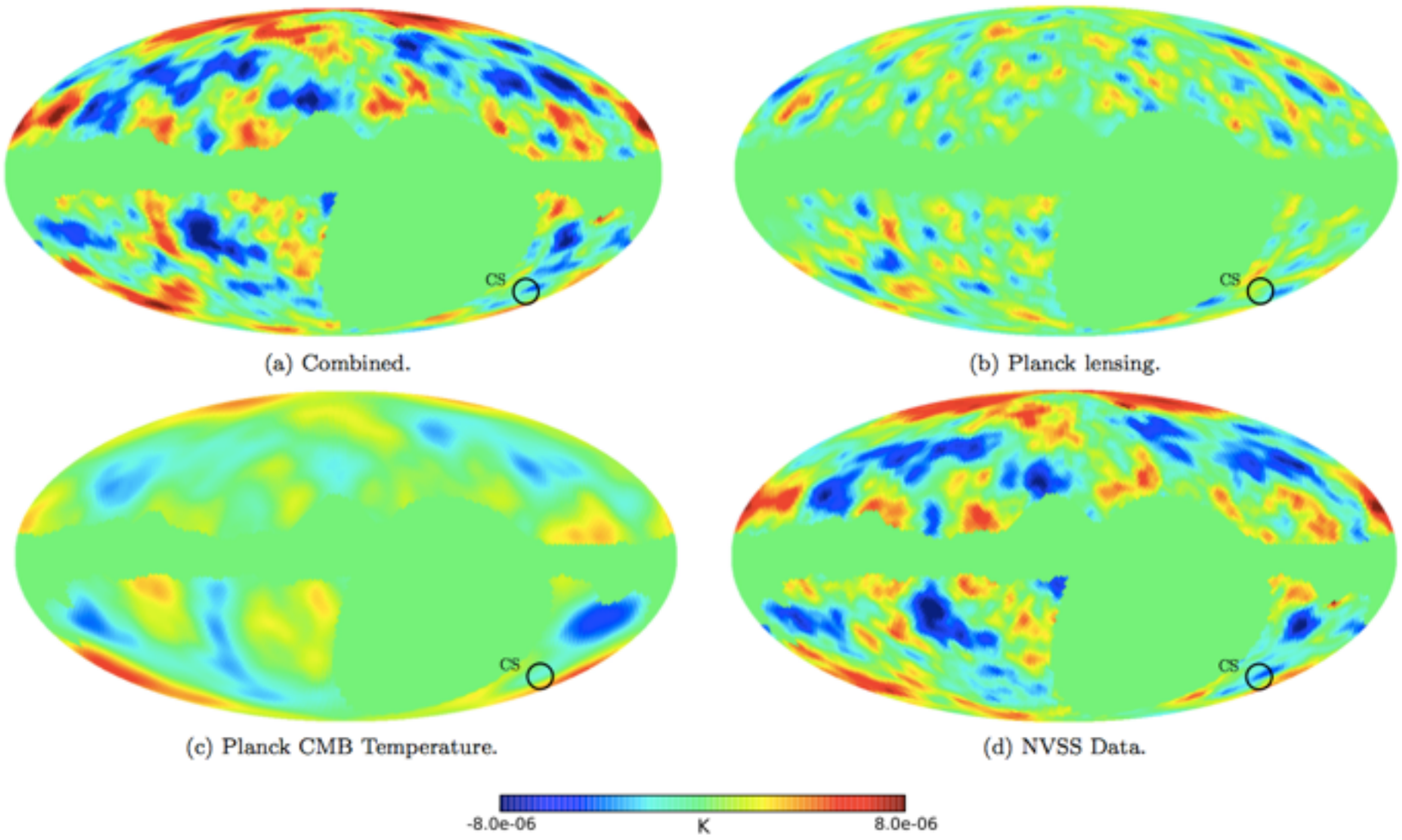


$$\mathcal{L}(T^{obs}|\text{theory})$$

ISW MAP

A. Manzotti, S. Dodelson,1407.5623

FULL SKY MAP OF THE ISW



(a) Combined.

(b) Planck lensing.

(c) Planck CMB Temperature.

(d) NVSS Data.

Galaxies are the most powerful tool.

Additional result: ISW is not enough to explain the Cold Spot !!

Lensing will help in the future.

A. Manzotti, S. Dodelson,1407.5623

2D-3D CORRELATION

Sam Passaglia, A. Manzotti S. Dodelson

2Dx2D Framework

We only have access to the 2D Projection:

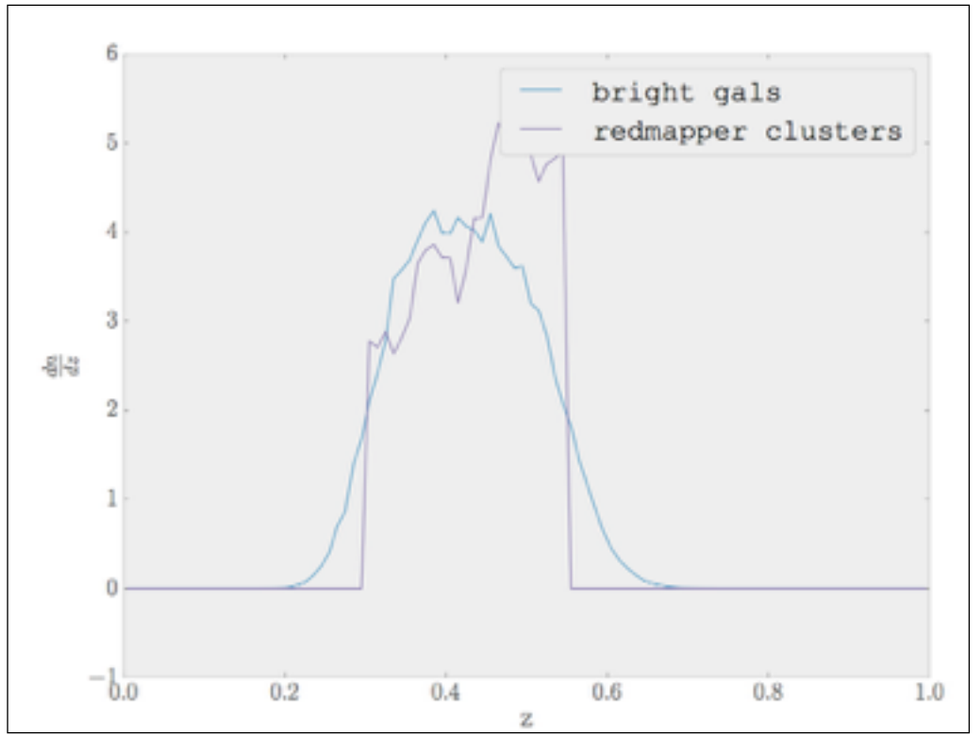
$$\widetilde{A}(\hat{n}) \equiv \int dr F_A(r) A(r\hat{n})$$

Expand in Spherical Harmonics

$$\widetilde{A}_{lm} = \int dr F_A(r) \int d\Omega Y^*_{lm}(\hat{n}) A(r\hat{n})$$

Convenient Result (in Limber Approximation)

$$\langle \widetilde{A}_{lm} \widetilde{B}_{lm} \rangle = C_l^{AB} = \int dk \frac{1}{l+\frac{1}{2}} P(k)\ F_A(\frac{l+\frac{1}{2}}{k}) F_B(\frac{l+\frac{1}{2}}{k})$$



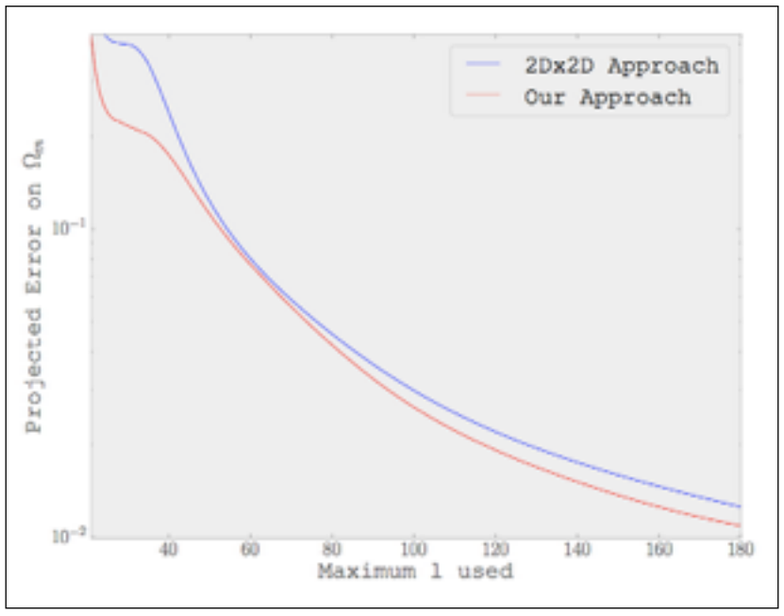
2D-3D

Sam Passaglia, A. Manzotti S. Dodelson

$$B_{lm}(q) = \int_0^\infty r^2 dr \int d\Omega Y^*_{lm}(\hat{n}) \sqrt{\frac{2}{\pi}} q j_l(qr) B(r, \hat{n})$$

$$C_{AB}(l,q) \equiv \langle \widetilde{A}_{lm} B^*_{l'm'}(q) \rangle = P_{AB}(q) \widetilde{D}_l(q) \frac{F_A(\frac{l+\frac{1}{2}}{q})}{\sqrt{l+\frac{1}{2}}} \delta^{l'}_{l} \delta^{m'}_{m}$$

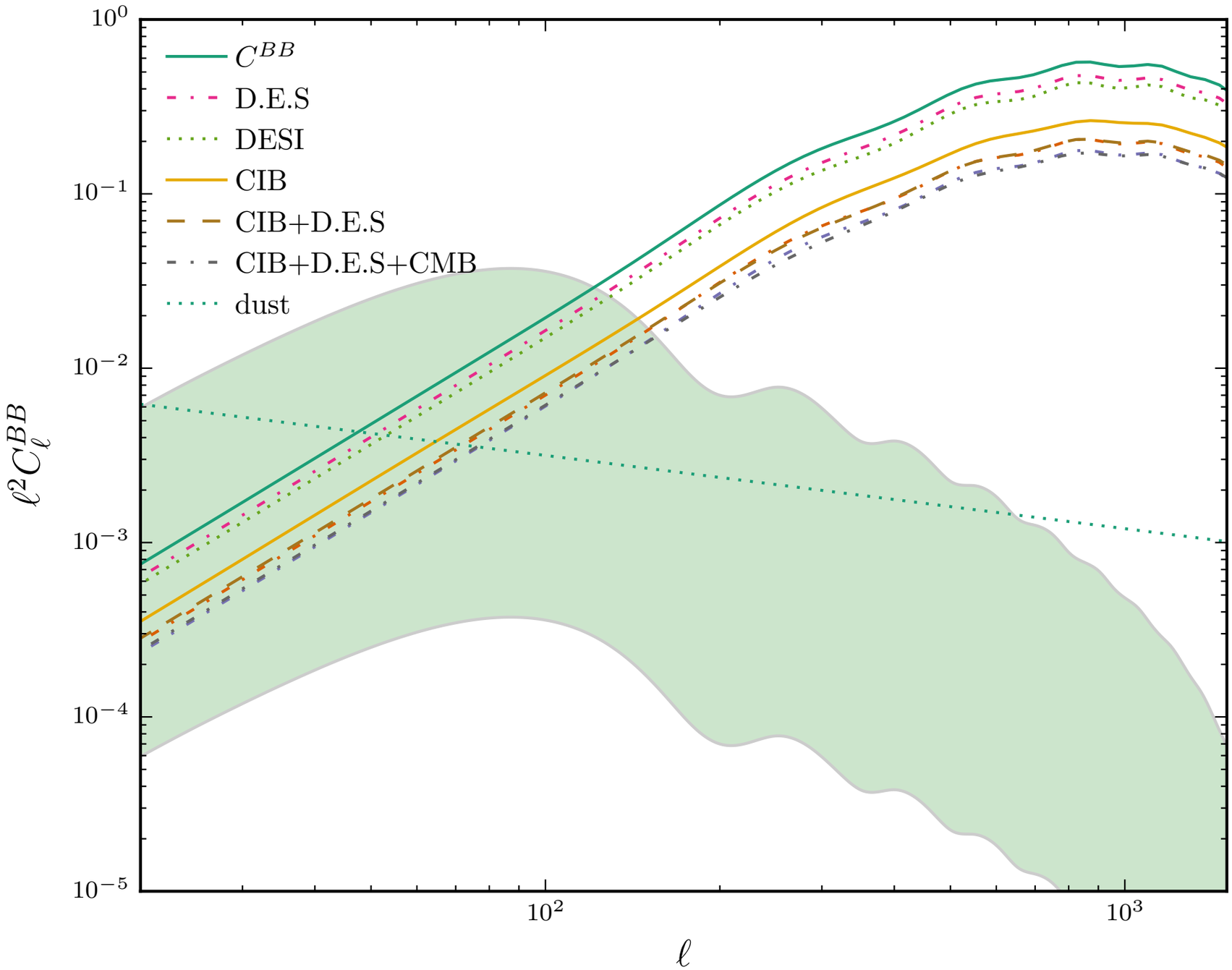
$$\hat{P}_{AB}(q_b) = \frac{1}{\Delta q_b} \int_{q \in q_b} \frac{1}{L} \sum_{l,m} \frac{1}{2\sqrt{l+\frac{1}{2}}} \frac{1}{F_A(\frac{l+\frac{1}{2}}{q})} \frac{1}{\widetilde{D}_l(q)} \langle \widetilde{A}_{lm} B^*_{lm}(q) \rangle$$



THANKS

Alessandro Manzotti (KICP-U. Chicago)

DELENSING: THEORETICAL FORECAST



OUR MAXIMUM LIKELIHOOD TECHNIQUE

$$T^{obs} = T^{prim} + T^{\rm ISW} + T^{n}$$

"cleaning part"

$$\mathcal{L}(T^{obs}|\text{theory}) \propto \frac{1}{\sqrt{\det(C)}} \exp\left\{-\frac{1}{2}\left(T^{obs} - T^{ISW}\right) C^{-1} \left(T^{obs} - T^{ISW}\right)\right\}$$

$$\times \frac{1}{\sqrt{\det\begin{pmatrix} C^{ISW} & C^{gT} \\ C^{gT} & C^{gg} \end{pmatrix}}} \exp\left\{-\frac{1}{2}\begin{pmatrix} T^{ISW} & \delta_g \end{pmatrix}\begin{pmatrix} C^{ISW} & C^{gT} \\ C^{gT} & C^{gg} \end{pmatrix}\begin{pmatrix} T^{ISW} \\ \delta_g \end{pmatrix}\right\}$$

"correlation part"

A. Manzotti, S. Dodelson

NO SURPRISE IT WILL LIMIT INFLATIONARY CONSTRAINTS AND MORE

- Our constraint on the **inflationary tensor** perturbation **amplitude and tilt** will depend on it

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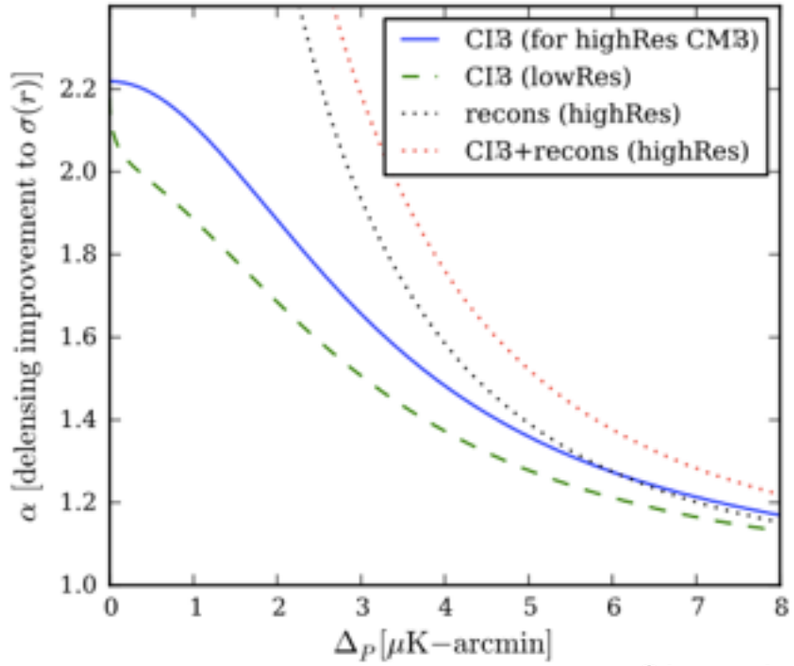
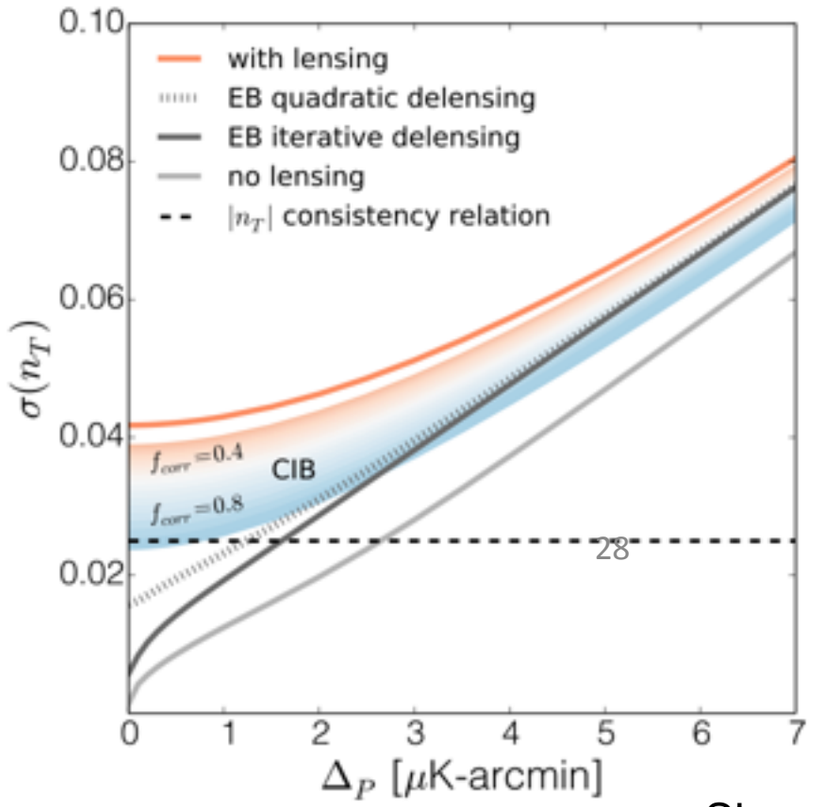


Sherwin Schmittfull.



Simard